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A risk-based definition of the confidence factor for the seismic assessment of URM existing buildings

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Abstract

The paper critically examines the current approach adopted in Standards to face the incomplete knowledge that constitutes one of challenging issue involving the seismic safety assessment of existing buildings. As known, the current approach is based on the confidence factors' approach, whose value is related to the knowledge level achieved, aimed at penalizing the verification procedure when knowledge is limited, thus leading to a more cautionary assessment. Such an approach is applied in the paper to a prototype representative of existing unreinforced masonry buildings, for which the possible uncertainties compatible with the different knowledge levels, according to the Standards definition, are considered. More specifically, the criteria recommended in the Italian Structural Code issued in 2018 and the directions outlined in the draft of Eurocode 8 (Part 3), that is currently under review, have been tested in the paper. To establish a reference solution to assess the reliability of these approaches, nonlinear static analyses are carried out to quantify the propagation of uncertainties by using a Monte Carlo sampling (100 models); the uncertainties deriving from the mechanical parameters or masses and those associated with drift are distinguished. Having verified the unreliability of the current approach, a practice-oriented procedure is proposed in the paper, based on a codified sensitivity analysis, which allows to derive the confidence factor from the dispersion of the outcome of the assessment, which is the input acceleration compatible with the limit state under verification. Therefore, the proposed procedure is consistent with a probabilistic safety check, even if based only on few deterministic evaluations.

Keywords: Confidence Factor; masonry existing buildings; seismic assessment; nonlinear static analysis; sensitivity analysis; Montecarlo sampling

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1. Introduction

The evaluation of the seismic safety of existing structures is strongly affected by the incomplete knowledge of the mechanical parameters of the materials and constructive details, after geometric and structural survey, as well as the diagnostic investigations (Franchin et al. (2010), Rota et al. (2014), Tondelli et al. (2012)). Mechanical parameters are affected by aleatory uncertainties related to limited reliability of in-situ tests and the difficulties in their interpretation, but also by the intra-building variability of these parameters. In the case of structural details, they are often hidden and their incomplete knowledge may sometimes affect the choice of model, thus introducing epistemic uncertainties whose role may be even more relevant than aleatory ones (e.g. see Cattari et al. (2022), Ottonelli et al. (2022)).

In Standards, depending on the knowledge level (KL) achieved, the problem is faced through the definition of confidence factors (CFs), to be considered in the verification procedure with the aim of penalizing it, (CEN (2005), NTC (2018), ASCE 41-17 (2017)). Indeed, these factors are established a priori, without really considering the propagation of uncertainties on the response, and are applied arbitrarily to the material strength parameters.

In this paper, the approaches adopted in the Italian Structural Code ((NTC, 2018) and its Illustrative Circular (Circolare (2019)) and that of the updated version of Eurocode 8-Part 3 (under review and synthetically named EC8-3_up in the following) are examined. Some basic principles of these Standards are briefly summarized in §2.

Various literature works (Rota et al. (2014), Haddad et al. (2019)) already highlighted the limitations of the current Standards approach. For example, in Rota et al. (2014) it has been proposed to apply the CF directly to the value of the seismic capacity compatible with the attainment of a given Limit State (LS). Instead, in Haddad et al. (2019), the CF is calculated through a probabilistic approach by equating the probability of exceeding the LS calculated with reference to a fragility curve whose parameters are estimated by a sensitivity analysis (by using a limited number of cases or a full factorial variation of the uncertain variables); so the CF is directly related to the actual dispersion of the building, obtained by considering uncertainties propagation.

In the paper, a 'risk-based' practice-oriented procedure is proposed based on a codified sensitivity analysis, which allows to derive the CF from the dispersion of the outcome of the assessment but on basis of a limited number of analyses. The verification proposal takes into account the incomplete knowledge and can reasonably be based on calculating, for different KLs, the probability of exceeding the LS and then assessing the peak ground acceleration value for which there is an equal probability of occurrence from the hazard curves. This approach ensures a consistent definition as KLs vary, because it takes into account for the actual residual dispersion. The risk-based procedure is applied in the paper to a case study representative of an existing unreinforced masonry (URM) building. Then, to assess the reliability of the proposed approach, a reference solution was defined by computing a fragility curve by performing nonlinear static analyses (NLSAs) on a set of models in which all parameters are described by their stochastic distribution and were assigned by employing the Monte Carlo sampling.

Nomenclature

URM	unreinforced masonry
CF	confidence factor
LS	limit state
NLSA	nonlinear static analysis
SLC	collapse limit state
KL	knowledge level
EC8-3_up	Eurocode 8 part 3 under review
γ_{Rd}	partial factor accounting for uncertainty proposed by EC8-3
a_g	peak ground acceleration
$a_{g,SLC}$	reference value of the peak ground acceleration
$a_{g,NTC/EC}$	peak ground acceleration according to Standards indications
$a_{g,v}$	peak ground acceleration associated to the materials dispersion
$a_{g,\theta}$	peak ground acceleration associated to the drifts dispersion
β	dispersion
β_v	dispersion associated with material uncertainty

β_θ	dispersion associated with drift uncertainty
β_{all}	dispersion associated with all variables uncertain

2. Basics of the approaches adopted in two Standards compared in the paper

Insights into the reliability of methods adopted in EC8-3_up and NTC18 (NTC (2018)) Standards have been done. Both Standards refer, as already mentioned in §1, to an approach based on the concept of the confidence factor CF (called γ_{Rd} by EC8-3).

In both cases, the Standards define three knowledge levels (KL1, KL2 and KL3), with increasing achieved knowledge; passing from the more limited (KL1) to the more detailed levels of knowledge (KL3), the CF (1.35/1.2/1) or γ_{Rd} (1.9/1.8/1.7) values are reduced. However, in the case of EC8-3_up, the coefficient γ_{Rd} is applied to the displacement capacity, obtained from the pushover curve using the average values of the mechanical properties of the materials; instead, in the case of NTC18 the CF is applied to the values of the mechanical properties, which are defined differently according to KL.

In the case of the new draft EC8-3_up, the γ_{Rd} coefficients proposed for the different KLs are very high and poorly differentiated with the KLs, because the uncertainty on the ultimate drift is not reduced by diagnostic investigations.

3. The proposed risk-based procedure for the definition of the confidence factor

A "risk-based" assessment procedure, similar to the one firstly proposed in Haddad et al. (2019), is proposed. It takes into account the incomplete knowledge by calculating, for different KLs, a CF to be applied to the median value of the peak ground acceleration (a_g) that gives the attainment of the LS, in order to have the same probability of occurrence of the LS (considering also the hazard curve in the site), independently by the achieved KL. Indeed, this approach ensures a consistent definition varying the KL because it accounts for the total probability of occurrence, without an explicit choice of a reference fractile for the capacity. This method therefore requires knowing: the Hazard curve, in particular its slope k; the median value of the fragility curve a_{g50}; the dispersion β, due to the residual uncertainties on the building capacity.

According to an engineering practice approach, a reliable estimation of a_{g50} and β may be obtained by performing a limited number of NLSA; if the number of independent variables is N, a practitioner can proceed by performing:

- 2N analyses: single parameter sensitivity analysis, performed by assigning the median value to all variables except one, for which the 16th or 84th percentile is assumed. Then, it can be derived the partial dispersions β_k (*k*=1,..N) of each uncertain parameter. By examining the values of β_k, it is possible to identify a number N'<N of the most significant parameters affecting the building response.
- $2^{N'}$ analyses: if a more accurate estimation is requested, a full factorial analysis may be performed by combining only the N' most significant variables in terms of propagation of uncertainties. Analyses are performed by combining altogether the 16th or 84th percentile values of the N' variables, which in the case of the logarithm of the variable corresponds to +1 or -1 times the β with respect to the median value. So, from each analysis it is obtained the capable acceleration and the partial dispersions β_k (*k*=1,..N') of each relevant uncertain parameter.

At this point, after the $2^{N'}$ analyses or eventually also on the basis of the 2N analyses, it is possible to calculate the total dispersion $\beta_{tot} = \sqrt{\sum \beta_k^2}$, the mean capable acceleration $a_{g,m}$ and the median capable acceleration $a_{g,50}$.

The steps of this procedure are summarised below:

- N uncertain parameters are identified.
- A sensitivity analysis is performed (2N analyses), based on ranges of values compatible with KL1.
- The N' most significant variables are selected and on these the KL is possibly improved, through specific survey.
- The final values are obtained and $2^{N'}$ analyses are performed, using median values for drift limits and obtaining: β_v, that is the dispersion associated with uncertain variables; $a_{g,v}$, that is the mean value of the seismic capacity.
- Similarly, the fragility parameters associated to the dispersion of drifts limits are estimated, e.g. β_θ and $a_{g,\theta}$.
- The overall fragility parameters are estimated, e.g. β and $a_{g,50}$

$$\beta = \sqrt{\beta_v^2 + \beta_\theta^2} \tag{1}$$

$$a_{g,50} = exp\left[\ln\left(\frac{1}{2}\left(a_{g,v} + a_{g,\theta}\right)\right) - \frac{1}{2}\beta^2\right] \tag{2}$$

- The acceleration to be used for verification, which accounts for the incomplete knowledge, is finally assessed using the risk-based approach:

$$a_g^* = \frac{a_{g,50}}{CF} \tag{3}$$

$$CF = e^{\frac{1}{2}\beta^2 k} \tag{4}$$

Therefore, the final outcome of the assessment is the seismic capacity a_g^* of a deterministic building for which the probability of occurrence of the LS is the same of the actual building, taking into account the residual uncertainties. If the knowledge level is low, the dispersion of the fragility curve is high, the CF is also higher and the seismic capacity a_g^*, to be compared with the reference seismic input, is lower, thus making the verification more conservative.

4. Reference solution for the validation of the proposed procedure at increasing knowledge levels

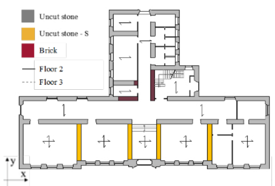
From a probabilistic point of view, a fragility curve is obtained for each model analysed, assimilable to a log-normal cumulative distribution defined by the median value of the peak ground acceleration a_{g50} and the dispersion β.

This curve is obtained by a Monte Carlo generation of M models, in which all parameters are described by their stochastic distribution, and by performing NLSAs. By improving the KL, the uncertainties on some parameters reduced, with a reduction of dispersion and a possible change of the median value. The procedure consists of:

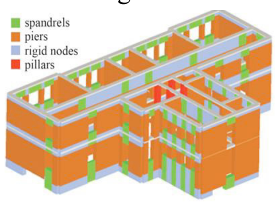
- definition of the reference parameters of the stochastic model and their probabilistic characterization to generate the representative sample of the KL1/KL2/KL3 knowledge levels;
- execution of nonlinear static analyses on the M models, obtaining the pushover curves and calculating for each one the acceleration compatible with the SLC (alternatively employing the conversion rules to the nonlinear equivalent single degree of freedom system provided by the NTC 2018 and by the EC8-3_up);
- drawing of numerical fragility curves for the building under consideration in that specific KL;
- calculation of the probability of occurrence of SLC by numerical integration of the convolution between the fragility and hazard curves, and evaluation of $a_{g,SLC}$ from the hazard curve;
- execution of the verification using the rules indicated by the aforementioned Standards, and comparison of the values of the acceleration at SLC, obtained by the different professionals, with the reference one ($a_{g,SLC}$) from a fully probabilistic approach, in order to check if the normative rules lead to consistently precautionary values;
- application of the proposed procedure (evaluation of a_g^*) and comparison with $a_{g,SLC}$.

5. Selected URM case study and adopted modelling approach

The case study is inspired by the URM school of Visso. The equivalent frame model was already available (Brunelli et al. (2021)) and validated thanks to a comparison between the simulated and actual damage suffered by the structure after the Central Italy 2016/2017 earthquake. The model has been realized using the Tremuri software package (Lagomarsino et al. (2013)), by assuming the presence of rigid diaphragms and a good wall-to-wall connection. The efficiency of this modelling strategy has been proved in the literature (Cattari et al. (2021), Lagomarsino et al. (2022)). With the aim of performing NLSAs according to basic principles recommended in the adopted Standards, the nonlinear behaviour of piers and spandrels has been described according to constitutive laws depicted in Figure 1.



a)



b)

Figure 1 – a) in plan view and b) 3D equivalent frame model of the selected case study.

Table 1 shows the maximum, mean and minimum values of mechanical parameters on which Monte Carlo sampling was done (assuming min and max as 16% and 84% percentiles); they consist of the Young (E) and shear (G) moduli and the compressive (f_m) and shear (τ_0) strength of masonry. The latter allow to interpret the flexural and diagonal shear cracking failure modes according to the criteria proposed in NTC (2018) and Turnšek and Sheppard (1980), whose main hypotheses are discussed in Calderini et al. (2009). The values were defined according to range of variation proposed in Table C8.5.I of Circolare (2019). Table 1 also shows the range of variation assumed for drift thresholds (θ_{DLi}), consistent with experimental evidences (e.g. Vanin et al. (2017), Rezaie et al. (2020)).

Table 1. Masonry type of Visso's school and associated mechanical parameters

Case Study	Masonry Type	f_m $[N/mm^2]$ min mean max	τ_0 $[N/mm^2]$ min mean max	E $[N/mm^2]$ min mean max	G $[N/mm^2]$ min mean max	θ_{4_shear} *Piers* min mean max	θ_{4_PF} *Piers* min mean max	θ_{4_shear} *Spaldrels* min mean max	θ_{4_PF} *Spandrels* min mean max
Visso building	Cut stone	2.6	0.0056	1500	500	0.0047	0.0074	0.1471	0.0172
		3.2	0.0398	1740	580	0.0050	0.0100	0.0150	0.0200
		3.8	0.0740	1980	660	0.0053	0.0126	0.0153	0.0228

The following conditions have been investigated (each one with 100 models stochastically generated):

- KL1/KL2/KL3: mechanical parameters (strength, stiffness and drift limits) generated stochastically, assuming that dispersion decreases as the KL increases.
- KL_bis: strength and stiffness parameters random; drifts kept constant and equal to the Standard values.
- KL4: mechanical strength and stiffness parameters deterministic and equal to the distribution's mean value; drifts random.

Moreover, two alternative structural details have been examined: A) weak spandrels (i.e. absence of tensile resistant element coupled to spandrels); C) reinforced concrete (RC) tie beams coupled to spandrels. They exemplify possible epistemic uncertainties that may affect the structural response (e.g. see Ottonelli et al. (2022)).

6. Results

The reliability of the proposed method and of those of Standards was verified by using as reference the numerical fragility curves based on analyses performed on the models generated by Monte Carlo sampling. In particular, the reference value of the acceleration $a_{g,SLC}$ is estimated by evaluating the probability of occurrence of SLC from the risk integral, using the numerical fragility obtained by the 100 models randomly generated and introducing a reference hazard curve; then, the value of the ground acceleration $a_{g,SLC}$ has been singled out from the adopted hazard curve.

6.1. Limitations of Standards' approaches

The verifications carried out according to the Standards indications do not require a rigorous calculation of the probability of occurrence of the SLC, because they carry out a single evaluation of $a_{g,NTC/EC}$. Figure 2 summarizes the results of $a_{g,NTC/EC}/a_{g,SLC}$ (when it is less than 1, the method is precautionary). Different outcomes of the verification may be obtained, depending on possible analysts' choice compatible with assumed parameters distributions.

The EC8-3_up approach provides almost always estimates on the safe side, while the NCT18 ratio is in several cases greater than 1. This is ascribable to the very high values of the coefficient γ_{Rd}, that in addition doesn't decrease so much with increasing KLs. Moreover, a critical issue is the representativeness of the result provided by a single NLSA, with all material parameters set to the mean value; the aim is to get a good estimate of the mean (or of the median) value of the seismic capacity, but errors are in some case significant (till to 25%).

The NTC18 method is quite unstable in guaranteeing a precautionary safety verification, especially for KL2. Moreover, a critical issue of NTC18, differently from EC8-3_up, is that NLSA is performed with "fractile" values of material parameters, because CF is applied to the masonry strength; therefore, the obtained collapse mechanism may be not representative of the prevailing behaviour, making the verification rather unstable. Moreover, even if seismic performance is mainly influenced by drift limits, the same values of EC8-3_up are assumed by NTC18, representative of the mean values, therefore CF is not applied to displacement capacity neither before nor after the analysis.

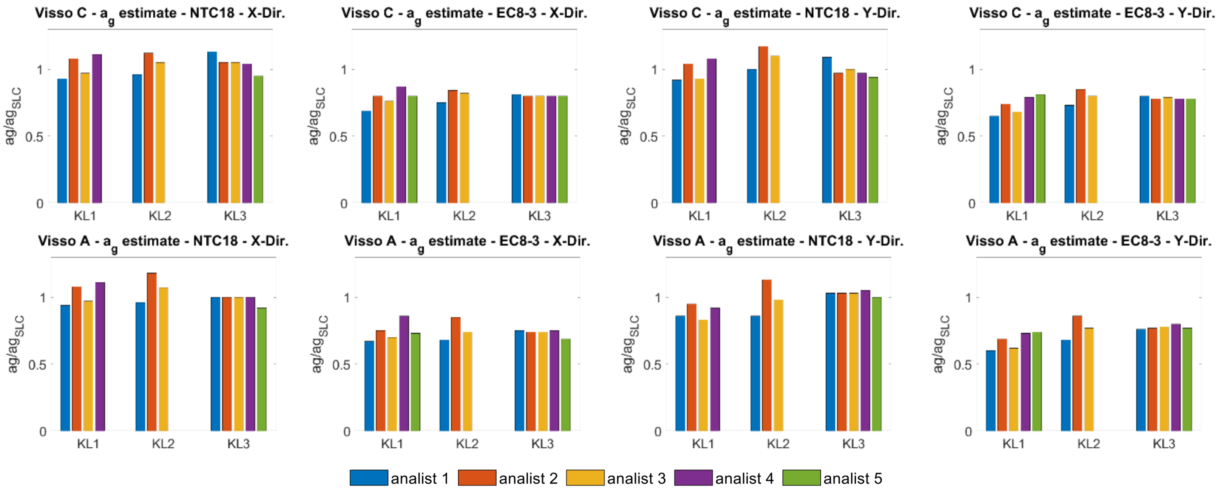


Figure 2 – Estimation of a_g using normative methods for building configurations inspired by the school of Visso

6.2. Results by using the risk-based approach

The sensitivity and factorial analyses have been applied to the case study, to estimate the dispersion and compare it with the values deduced from Monte Carlo analyses. The dispersion was evaluated:

- from the results of the models named KL4, in which mechanical parameters are assumed deterministic and the only aleatory variable considered is drift;
- for each KL, by evaluating the dispersion (β_{all}) from the results of the models in which all variables are random and the one (β_v) obtained by the models in which the drift limits are constant to the mean value (by assuming the different contributions as statistically independent, $\beta_\vartheta = \sqrt{\beta_{all}^2 - \beta_v^2}$);
- for each KL, by using the factorial analysis.

As expected, the KL does not affect the contribution to the dispersion associated with the drift. Moreover, the drift obtained from the factorial analyses is in very good agreement with that obtained from the numerical fragility curves. Finally, slightly different values were found for each building and in the two directions (e.g. β_ϑ is about 0.2 for Visso A and 0.18 for Visso C in the X direction, while lower and less uniform values were obtained in Y direction).

The dispersion contribution associated with material uncertainty (β_v) is shown in Figure 3. It emerges that:

- the dispersion decreases progressively from KL1 to KL3 ($KL1_{bis}$ and $KL3_{bis}$);
- the material-related dispersion is well estimated by the factorial analysis ($KL_{fact\text{-}mat}$); in most of the cases, the dispersion estimated from the factorial analysis is slightly greater than that obtained from Monte Carlo sampling, which is in favour of safety and is consistent with the assumption of uncorrelation in the factorial analyses.

The X-direction again shows more regular results than the Y-direction. Anyhow, factorial analyses appear to be an efficient tool for estimating dispersion associated with material uncertainty.

Finally, the total dispersion was investigated, as illustrated in Figure 4. It can be seen that:

- for each KL, comparing the estimated values from numerical fragility curves and factorial analysis, a very good agreement is observed.
- dispersion does not reduce so much for higher levels of knowledge because the drift-related dispersion remains constant; again, results in the Y-direction are less regular.

In conclusion, the factorial analysis provides reliable estimate of β_{all}. However, if the method should be implemented in the engineering practice possibly at Standard level, it is suggested to assume the following lower bound values, considering that in the assessment some additional uncertainties might be neglected:

$$\beta_\theta \geq 0.25 \quad \beta_\theta \geq \begin{cases} 0.5 - KL1 \\ 0.3 - KL2 \\ 0.1 - KL3 \end{cases} \rightarrow \beta_{all} \geq \begin{cases} 0.56 - KL1 \\ 0.39 - KL2 \\ 0.27 - KL3 \end{cases} \tag{5}$$

With these choices, the CF values become at least equal to (k=2.5 is assumed for the hazard curve):

$$CF \geq \begin{cases} 1.48 - KL1 \\ 1.21 - KL2 \\ 1.09 - KL3 \end{cases} \tag{6}$$

Finally, the factorial analysis' estimate of a_{g50} is shown in Figure 5, which reports the error made with respect to the value taken from the numerical fragility curves from Monte Carlo sampling. The errors are very low, with a maximum of 20%.

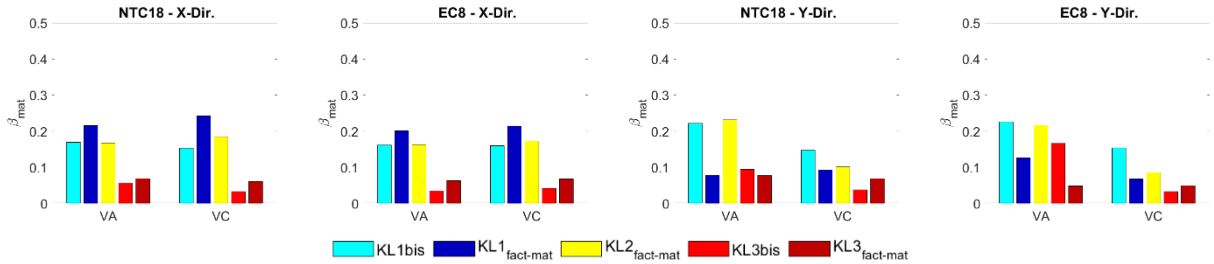


Figure 3 – Material-related dispersion at varying KL for the Visso models

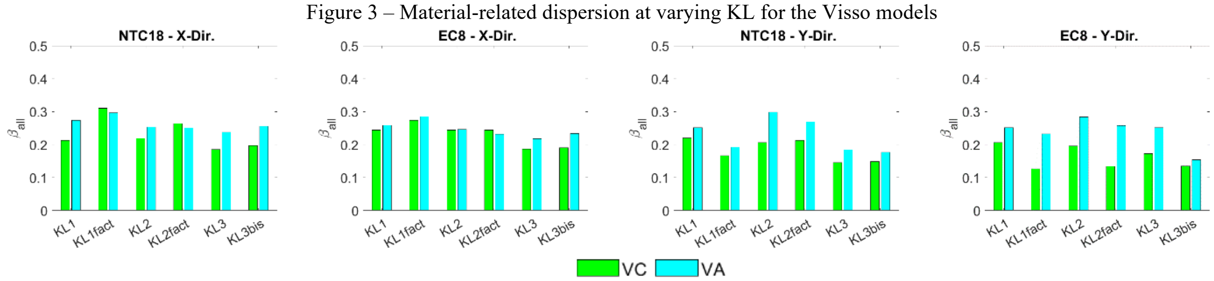


Figure 4 – Total drift and material-related dispersion β_{all}, varying models for different KLs

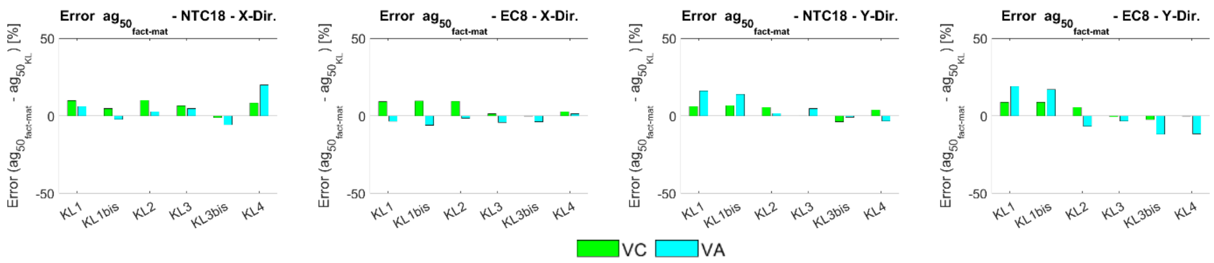


Figure 5 – Error in the estimation of the a_{g50} using factorial analysis in the two models of Visso's school for different KLs.

7. Conclusions

The seismic assessment of existing masonry buildings is a complex task, strongly dependent from the uncomplete knowledge residual after survey and investigations. Standards usually refer to a classification into three different KLs to which a CF is associated, to be used in the verification as a sort of safety coefficient. Indeed, the uncomplete knowledge results in an increase of uncertainties, that increase the probability of exceedance of the considered LS.

Two case-study buildings have been selected, and different possible knowledge levels were considered. The results provided by adopting two Standards, NTC18 and EC8-3_up, have been compared and validated with those obtained by a Monte Carlo sampling and a fully probabilistic risk evaluation, assumed as reference solution.

A more robust "risk-based" procedure (Haddad et al. (2019)) has been also considered and refined, in order to be easily implemented at engineering-practice level. It makes use of a sensitivity analysis, very useful to single out the relevant parameters to be investigated, and to estimate the median value and the dispersion of the seismic capacity.

The results obtained showed that:

- NTC 2018: the method is generally conservative at KL1, while being overly optimistic in KL2 and KL3 cases. Furthermore, the application of CF to strength parameters can lead to the estimation of a collapse mechanism that is not representative of the prevailing seismic behavior of the building.

- EC8-3 under review: the partial factor γ_{Rd} applied to the displacement capacity of the structure are quite high and produce a largely precautionary estimate. The fact that these factors do not reduce significantly with the KL is consistent with the fact that the dispersion in the drift limits cannot be reduced with investigations.
- "risk-based" procedure: the use of factorial analysis is efficient in estimating with small error both parameters of the numerical fragility curve obtainable more rigorously by Monte Carlo sampling.

Conflicts of interest/Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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